Spatiotemporal variation and correlation of soil enzyme activities and soil physicochemical properties in canopy gaps of the Tianshan Mountains, Northwest China

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Abstract: The study of the heterogeneity of soil enzyme activities at different sampling locations in canopy gaps will help understand the influence mechanism of canopy gaps on soil ecological processes. In this paper, we analyzed the spatiotemporal variation of soil enzyme activities and soil physicochemical properties at different sampling locations (closed canopy, expanded edge, canopy edge, gap center) in different sampling time (December, February, April, June, August, and October) on the northern slope of the Tianshan Mountains, Northwest China. The results showed that soil catalase, cellulase, sucrase, and acid phosphatase activities were relatively high from June to October and low from December to April, and most of soil enzyme activities were higher at closed canopy than at gap center. Soil urease activity was high during December–February. The soil temperature reached the highest value during June–August and was relatively high at gap center in October, December, and February. Soil water content was significantly higher in December and April than in other months. Soil bulk density was higher at gap center than at closed canopy in December. Soil pH and soil electrical conductivity in most months were higher at closed canopy than at gap center. Soil organic carbon, soil total nitrogen, and soil total phosphorus were generally higher at gap center than at closed canopy. Furthermore, sampling time played a leading role in the dynamic change of soil enzyme activity. The key factors affecting soil enzyme activity were soil temperature and soil water content, which were governed by canopy gaps. These results provide important support for further understanding the influence mechanism of forest ecosystem management and conservation on the Tianshan Mountains.

Keywords: soil enzyme activity; soil physicochemical property; spatiotemporal variation; canopy gap; Tianshan Mountains

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1 Introduction

Canopy gap is a window in the forest caused by tree cutting or the death of a forest community. As a kind of small- and medium-scale disturbance, canopy gaps widely exist in forest ecosystems (Wang et al., 2018) and have become a key force in promoting forest regeneration

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and ecological function improvement projects (Muscolo et al., 2014). The formation of canopy gaps changes the microenvironment (Anderegg et al., 2015) inside the forest, improves the spatial structure of soil pores, and leads to changes in ecological factors, such as microtopography, light, temperature, humidity, and soil nutrients status, resulting in a heterogeneous microclimate and rich ecological differentiation. Thus, canopy gaps have a complex impact on forest aboveground and underground ecosystems (Schliemann and Bockheim, 2014; Xu et al., 2016). The existence of canopy gaps creates spatial variation in soil physicochemical properties. Studies have shown that changes in soil physicochemical properties significantly influence soil microbial community structure (Strickland et al., 2017), substrate diffusion (Koch, 1990), and substrate availability (Ren et al., 2020), thus indirectly affecting soil enzyme activities (Wang et al., 2013; Chen et al., 2017). Soil enzymes are metabolic factors associated with soil organisms, which reflect the dynamic changes of soil nutrients and the material transformation and fertility of soil (Wang et al., 2016; Liu et al., 2021). Soil catalase is a representative enzyme of oxidoreductase, which participates in the material transformation and energy conversion of soil (Hentschel et al., 2008; Qiu et al., 2019). Among the hydrolases, soil cellulase and sucrase are related to soil carbon cycle (Cheng et al., 2020; Zhang et al., 2021). Soil urease and acid phosphatase are involved in the soil nitrogen and phosphorus cycles, respectively (Geisseler et al., 2010; Qiu et al., 2019). Forest soil enzymes are the most active bioactive substances in the underground ecological processes of terrestrial ecosystems and are sensitive to external interference. These enzymes participate in almost all biochemical reactions in soil, control the transformation of complex compounds in the underground ecological processes, and play an important role in nutrients cycling and energy transfer (He et al., 2019; Farooq et al., 2021). Canopy gaps lead to changes in local light and heat resources, thus changing the vegetation distribution pattern and soil environment, resulting in spatiotemporal heterogeneity of soil enzyme activities and soil physicochemical properties (Stan and Daniels, 2014). However, it is unclear which soil physicochemical properties play a crucial role in affecting the change of soil enzyme activities in canopy gaps.

Under the background of global climate change, the mid- and high-latitude mountain forest ecosystems have undergone complex and diverse changes, especially in winter and during growing seasons. Canopy gaps affect snow redistribution and the melting rate of snow cover in winter through canopy shading. The snow cover forms a gradient of different thicknesses from canopy gaps to closed canopy. Adiabatic effect of snow cover under canopy gaps in winter is conducive to maintaining high soil biological activity. The low temperature and freeze-thaw action in the snow-free covered area under closed canopy leads to high heterogeneity of soil environment (Li et al., 2015). The heterogeneous environment generated by canopy gaps not only influences the forest ecosystem in winter (Scharenbroch and Bockheim, 2007), but also affects the soil physical, chemical, and biological factors of the forest ecosystem in summer due to strong direct sunlight and intense transpiration (Schliemann and Bockheim, 2014; Xu et al., 2016). Yang et al. (2017) found that the driving factors leading to the change of soil enzyme activities in canopy gaps were soil dissolved organic carbon and nitrogen. Wang et al. (2021) reported that soil enzyme activities decreased with the increase of soil temperature and water content. Therefore, it is of great scientific significance to explore the spatiotemporal variation and correlation of soil enzyme activities and soil physicochemical properties in canopy gaps, which can promote the healthy development of forest soil ecosystems and provide a theoretical basis for the management and protection of forest ecosystems.

The Tianshan Mountains in Xinjiang Uygur Autonomous Region of China are the largest mountain system in Central Asia. *Picea schrenkiana* is the main tree species in the Tianshan Mountains, which constitutes the main body of the Tianshan Mountains forests (Lan et al., 2019), playing an irreplaceable role in accumulating water, maintaining soil, fixing carbon and releasing oxygen, and maintaining oasis stability in arid regions. From November to April every year, the Tianshan Mountains is covered with snow. The existence of canopy gaps leads to the formation of snow cover patches with different thicknesses in the forest (Chen et al., 2021). The change of soil

physicochemical properties may affect soil enzyme activities involved in soil ecological processes and other physicochemical properties, but the effect and mechanism are still unclear. In this paper, we analyzed the spatiotemporal variation and correlation of soil enzyme activities and soil physicochemical properties in the Tianshan Mountains. We hypothesized that (1) the spatiotemporal variation will change soil enzyme activities and soil physicochemical properties; (2) under the combined action of different canopy gap locations and sampling time, the change of sampling time has a great impact on soil enzyme activities; and (3) soil enzyme activities are closely related to soil physicochemical properties.

2 Materials and methods

2.1 Study area

The study area (43°29′37″N, 87°11′31″E) is located in the middle mountain zone on the northern slope of the Tianshan Mountains, Urumqi County, Xinjiang Uygur Autonomous Region of China, with an altitude of 1930 m a.s.l. The area has a temperate continental climate with an annual average temperature of 2.1 °C and an average annual precipitation of 176 mm (Chen et al., 2021). The snowfall in winter accounts for more than 20% of the annual precipitation, and the snow cover lasts for 5–6 months.

2.2 Experimental design and soil sampling

In the study area, we choose three sites with similar altitude, slope, and soil type. The site had an area of 20 m×20 m, with at least 500 m from each other. Then, we set up four quadrats with an area of 2 m×2 m for each at each site from closed canopy to gap center (i.e., closed canopy, expanded edge, canopy edge, gap center) to explore the spatial variation of soil enzyme activities and soil physicochemical properties. In order to clarify the temporal variation of soil enzyme activities and soil physicochemical properties, we collected soil samples at a depth of 0–20 cm every two months from December 2017 to October 2018, with three replicates of each soil samples. Finally, a total of 216 soil samples were collected in this study. The soil samples were sent back to the laboratory to remove roots, plant residues, and stones. We divided the soil samples into two subsamples; the first subsample was placed in a refrigerator at 4 °C to determine soil enzyme activities, and the second subsample was dried to measure the soil physicochemical properties.

2.3 Laboratory analyses

We determined soil enzyme activities according to Guan (1986). Specially, soil catalase, urease, and acid phosphatase were determined by KMnO4 titration method, phenol-sodium hypochlorite colorimetry method, and disodium phenyl phosphate colorimetry method, respectively; and soil cellulose and sucrase was measured by 3,5-dinitrosalicylic acid colorimetry method. Then, we calculated the soil enzyme activities based on Guan (1986) Furthermore, soil physicochemical properties were also determined. Specifically, soil temperature was analyzed with a button type temperature recorder (DS1923-F5, Maxim Integrated Products, Texas, USA). According to the study results conducted by Zheng (2013), we determined other soil physicochemical properties. Soil water content, bulk density, pH, and electrical conductivity were measure by drying method, cutting ring method, potentiometric method, and conductivity method, respectively. We determined soil organic carbon, total nitrogen, and total phosphorus according to Bao (2000). Potassium dichromate oxidation method was used to determine soil organic carbon, soil total nitrogen was determined by Kjeldahl method, and soil total phosphorus was measured using molybdenum antimony colorimetric method.

2.4 Statistical analyses

Excel 2019 and Origin 2018 were used for data processing and visualization, and SPSS v.23.0 and CANOCO v.4.5 were used for statistical analysis. We used one-way analysis of variance

(ANOVA), two-way ANOVA, and least significant difference (LSD) method to test the spatiotemporal variation of soil enzyme activities and soil physicochemical properties. CANOCO v.4.5 was used to analyze the correlation between soil enzyme activities and soil physicochemical properties. We used the detrended correspondence analysis (DCA) to detect the influence of soil physicochemical properties on soil enzyme activities, and the result showed that there was a linear relationship between soil physicochemical properties and soil enzyme activities. Therefore, a linear model was used for redundancy analysis (RDA). The importance of soil physicochemical properties was ranked using the Monte Carlo test, and the expansion coefficients of soil physicochemical properties were all less than 20, indicating the contribution rates of each soil property to the model were not repeated. Therefore, all the soil physicochemical properties, including soil temperature, soil water content, bulk density, pH, electrical conductivity, soil organic carbon, total nitrogen, and total phosphorus, were selected to evaluate their relationship with soil catalase, cellulase, sucrase, urease, and acid phosphatase activities.

3 Results

3.1 Spatiotemporal variation of soil enzyme activities

Figure 1 showed the spatiotemporal variation of soil enzyme activities. For the temporal variation of soil enzyme activities, soil catalase activity was higher in June and August, significantly higher than that in other months (P<0.05), and the lowest in April. Soil cellulase activity in August and October was higher than that in other months (P<0.05). Soil sucrase activity was the highest in August, but lower in December and February. Soil urease activity in December and February was significantly higher than that in other months, and there was no significant difference in June, August, and October. Soil acid phosphatase activity was the highest in August and the lowest in April. For the spatial variation of soil enzyme activities, at the same sampling time, soil catalase activity was relatively high at closed canopy and gap center in June and August. Soil cellulase activity at closed canopy and extended edge was higher than that at canopy edge and gap center in December, February, and August. Soil sucrase activity at closed canopy was higher than that at gap center in August. Soil urease activity at gap center was significantly higher than that at closed canopy in December, February, June, and October. Soil acid phosphatase activity was the lowest at gap center in October.

Soil enzyme activities were affected by sampling time, sampling location, and their interaction (Table 1). Firstly, the effects of sampling time on soil enzyme activities were extremely significant (P<0.01), indicating that soil enzyme activities were influenced by sampling time. Secondly, sampling location had various effects on soil enzyme activities. Specifically, there were an extremely significant relationship of sampling location with soil catalase, cellulose, and urease activities (P<0.01), a significant relationship between sampling location and soil sucrase activity (P<0.05), and no significant relationship between sampling location and soil acid phosphatase activity (P>0.05). Thirdly, the interaction between sampling time and location had extremely significant effects on soil cellulase, urease, and acid phosphatase activities (P<0.01), and had significant effects on soil catalase and sucrase activities (P<0.05). Finally, the results of two-way ANOVA revealed that soil enzyme activities were more affected by sampling time than by sampling location. It can be seen that sampling time played a leading role in the dynamic change of soil enzyme activities.

3.2 Spatiotemporal variation of soil physicochemical properties

Figure 2 showed the spatiotemporal variation of soil physicochemical properties. For the temporal variation of soil physicochemical properties, soil temperature was significantly higher in June and August than in other months (P<0.05). Soil water content in December and April was higher than that in other months (P<0.05). Soil bulk density was the highest in April. Soil pH in June and August was higher than that in December and October. Soil electrical conductivity was the lowest in June. Soil organic carbon and total nitrogen changed little throughout the year. Soil total

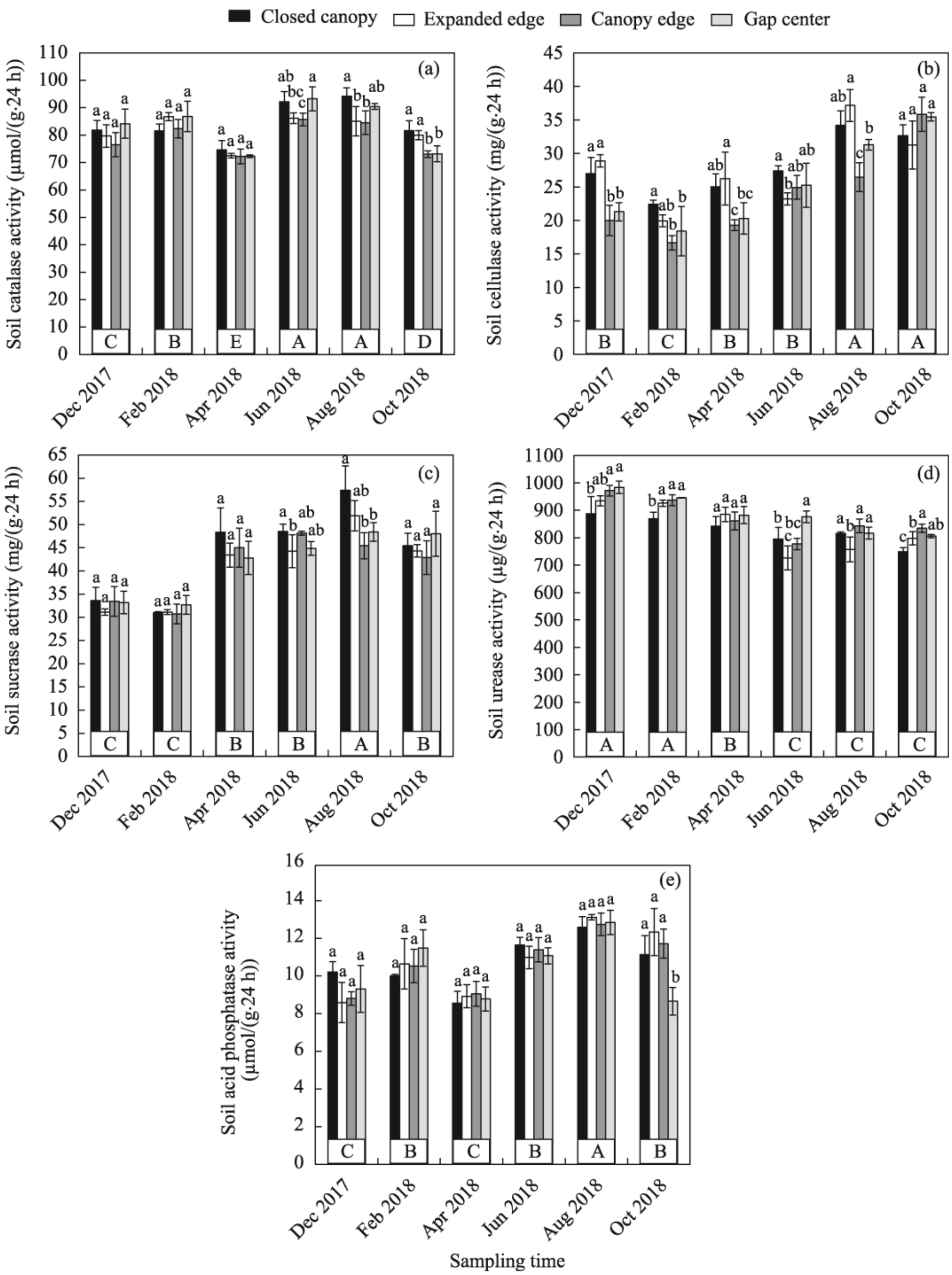

Fig. 1 Spatiotemporal variation of soil enzyme activities. (a), soil catalase activity; (b), soil cellulase activity; (c), soil sucrase activity; (d), soil urease activity; (e), soil acid phosphatase activity. Different lowercase letters represent the significant differences among the four sampling locations (closed canopy, expanded edge, canopy edge, gap center) at the same sampling time (P<0.05), and different uppercase letters represent the significant difference among sampling time (P<0.05). Bars mean standard errors.

phosphorus content was higher in February, June, and October. For the spatial variation of soil physicochemical properties, at the same sampling time, soil temperature was relatively high at gap center in October, December, and February. Soil bulk density at gap center and canopy edge was significantly higher than that at closed canopy and expanded edge in December (P<0.05).

Table 1 Effects of sampling time, sampling location, and their interaction on soil enzyme activities

Controlled variable	Observed variable	*df*	Sum of square	Mean of square	*F* value	Partial η^2
Sampling time	Soil catalase activity	5	2542.18	508.44	45.03^{**}	0.82
	Soil cellulase activity	5	1899.15	379.83	84.31^{**}	0.90
	Soil sucrase activity	5	3735.42	747.08	84.94^{**}	0.90
	Soil urease activity	5	260,504.71	52,100.94	65.75^{**}	0.87
	Soil acid phosphatase activity	5	126.34	25.27	42.93^{**}	0.82
Sampling location	Soil catalase activity	3	287.40	95.80	8.49^{**}	0.35
	Soil cellulase activity	3	221.71	73.91	16.41^{**}	0.51
	Soil sucrase activity	3	115.79	38.60	4.39^{*}	0.22
	Soil urease activity	3	40,600.06	13,533.35	17.80^{**}	0.52
	Soil acid phosphatase activity	3	1.827	0.61	1.04	0.06
Sampling time×Sampling location	Soil catalase activity	15	401.44	26.77	2.37^{*}	0.43
	Soil cellulase activity	15	362.44	24.16	5.36^{**}	0.63
	Soil sucrase activity	15	281.62	18.78	2.14^{*}	0.40
	Soil urease activity	15	48,513.34	3234.22	4.08^{**}	0.56
	Soil acid phosphatase activity	15	31.30	2.09	3.55^{**}	0.53

Note: *df*, degree of freedom. **, $P<0.01$ level, *, $P<0.05$ level.

Soil pH was higher at expanded edge and closed canopy but it was relatively lower at gap center. Soil electrical conductivity was relatively high at closed canopy in October, December, February, and April. Soil organic carbon and total nitrogen at gap center were higher than those at closed canopy. In most months, soil total phosphorus at gap center was higher, while that at closed canopy was lower.

Soil physicochemical properties were also affected by sampling time, sampling location, and their interaction (Table 2). Firstly, except for soil total nitrogen, sampling time had significant effects on soil physicochemical properties ($P<0.05$). Secondly, sampling location had various effects on soil physicochemical properties. Specifically, there was an extremely significant relationship between sampling location and soil pH, soil electrical conductivity, soil organic carbon, soil total nitrogen, and soil total phosphorus ($P<0.01$), a significant relationship of sampling location with soil water content and soil bulk density ($P<0.05$), and no significant relationship between sampling location and soil temperature ($P>0.05$). Thirdly, the interaction of sampling time and location had extremely significant effects on soil bulk density, soil pH, and soil electrical conductivity ($P<0.01$), and significant effects on soil total phosphorus ($P<0.05$). Finally, results of two-way ANOVA revealed that the influence of sampling location on soil pH, soil organic carbon, and soil total nitrogen was greater than that of sampling time.

3.3 Correlation analysis between soil enzyme activities and soil physicochemical properties

According to the results of RDA and correlation heat map between soil enzyme activities and soil physicochemical properties, we can conclude that soil temperature, soil water content, and soil bulk density had a good explanation for the change of soil enzyme activities (Fig. 3). Soil catalase, cellulase, sucrase, and acid phosphatase activities were positively correlated with soil temperature and soil pH. There was a significant positive correlation between soil acid phosphatase activity and soil total phosphorus. Soil urease activity was positively correlated with soil water content, soil bulk density, and soil electrical conductivity. Soil catalase, cellulase, sucrase, and acid phosphatase activities were negatively correlated with soil water content and soil bulk density. Soil catalase and acid phosphatase activities were significantly negatively correlated with soil electrical conductivity and soil organic carbon. Soil urease activity was negatively correlated with soil temperature and soil pH and negatively correlated with soil total phosphorus.

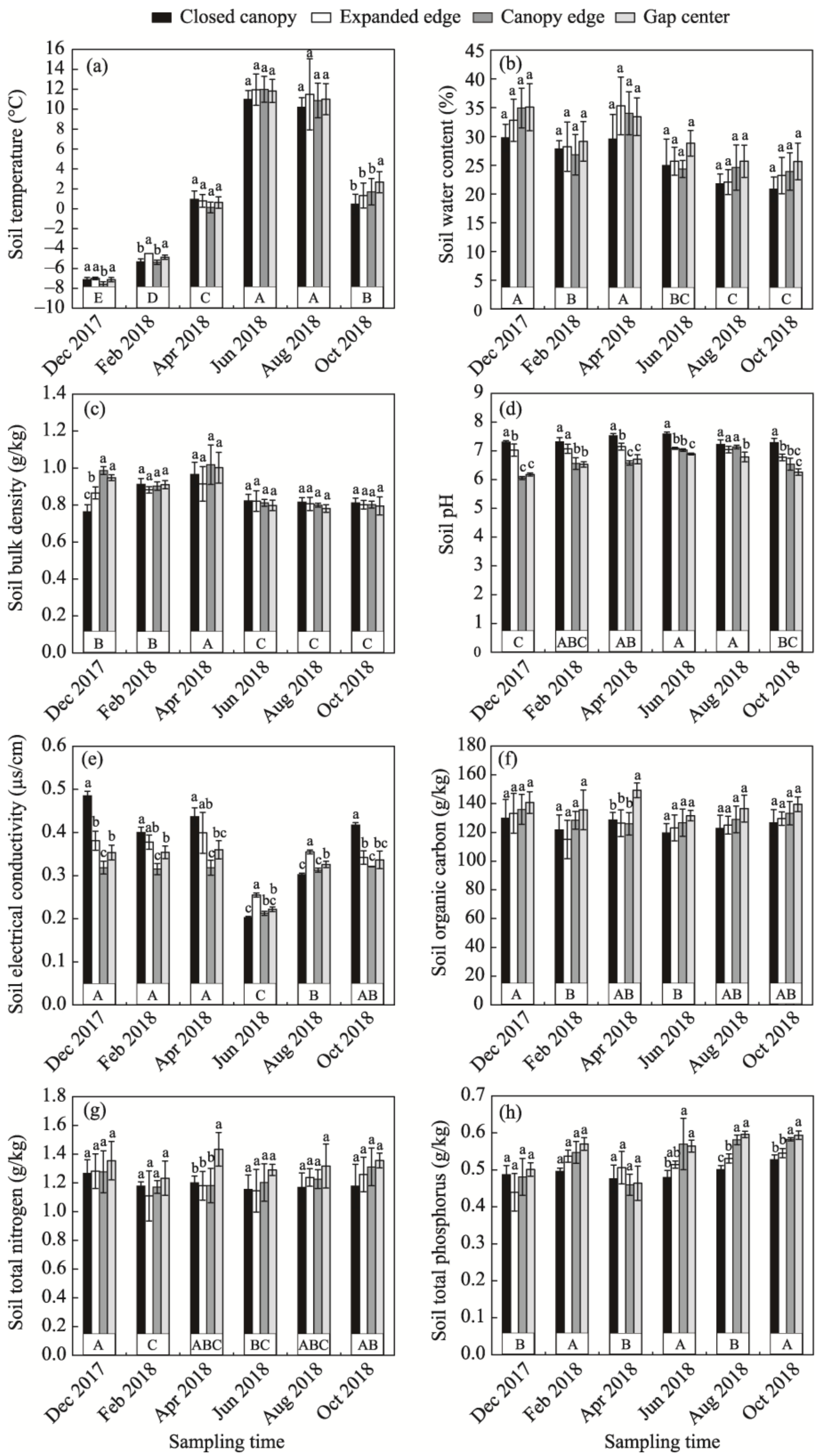

Fig. 2 Spatiotemporal variation of soil physicochemical properties. (a), soil temperature; (b), soil water content; (c), soil bulk density; (d), soil pH; (e), soil electrical conductivity; (f), soil organic carbon; (g), soil total nitrogen; (h), soil total phosphorus. Different lowercase letters represent the significant differences among the four sampling locations at the same sampling time ($P<0.05$), and different uppercase letters represent the significant difference among sampling time ($P<0.05$). Bars mean standard errors.

Table 2 Effects of sampling time, sampling location, and their interaction on soil physicochemical properties

Controlled variable	Observed variable	*df*	Sum of square	Mean of square	*F* value	Partial η^2
Sampling time	Soil temperature	5	3711.90	742.38	540.25**	0.98
	Soil water content	5	1170.31	234.06	21.60**	0.69
	Soil bulk density	5	0.30	0.06	29.35**	0.75
	Soil pH	5	2.31	0.46	30.27**	0.76
	Soil electrical conductivity	5	0.21	0.04	239.86**	0.96
	Soil organic carbon	5	1011.43	202.29	2.48*	0.21
	Soil total nitrogen	5	0.13	0.03	2.10	0.18
	Soil total phosphorus	5	0.09	0.02	20.33**	0.68
Sampling location	Soil temperature	3	5.58	1.86	1.35	0.08
	Soil water content	3	134.69	44.90	4.14*	0.21
	Soil bulk density	3	0.02	0.01	3.14*	0.16
	Soil pH	3	7.60	2.53	165.88**	0.91
	Soil electrical conductivity	3	0.06	0.02	106.31**	0.87
	Soil organic carbon	3	2267.54	755.85	9.26**	0.37
	Soil total nitrogen	3	0.22	0.07	5.88**	0.27
	Soil total phosphorus	3	0.03	0.01	12.96**	0.45
Sampling time×Sampling location	Soil temperature	15	9.80	0.65	0.48	0.13
	Soil water content	15	88.39	5.89	0.54	0.15
	Soil bulk density	15	0.09	0.01	3.05**	0.49
	Soil pH	15	1.77	0.12	7.75**	0.71
	Soil electrical conductivity	15	0.05	0.00	19.65**	0.86
	Soil organic carbon	15	595.43	39.70	0.49	0.13
	Soil total nitrogen	15	0.08	0.01	0.43	0.12
	Soil total phosphorus	15	0.03	0.00	2.27*	0.41

Note: *df*, degree of freedom. **, *P*<0.01 level, *, *P*<0.05 level.

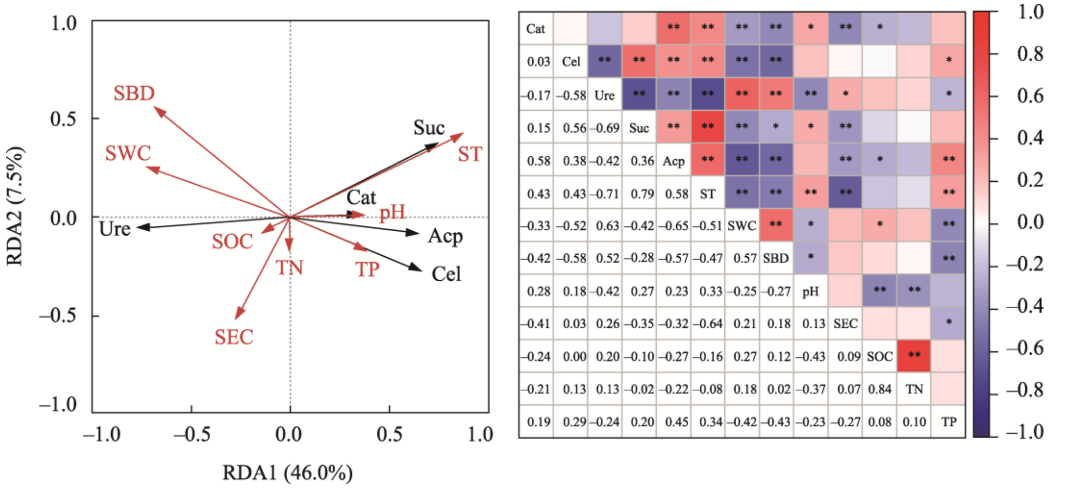

Fig. 3 Redundancy analysis (RDA, a) and correlation heat map (b) between soil enzyme activities and soil physicochemical properties. Cat, soil catalase activity; Cel, soil cellulase activity; Ure, soil urease activity; Suc, soil sucrase activity; Acp, soil acid phosphatase activity; ST, soil temperature; SWC, soil water content; SBD, soil bulk density; pH, soil pH; SEC, soil electrical conductivity; SOC, soil organic carbon; TN, soil total nitrogen; TP, soil total phosphorus. **, *P*<0.01 level; *, *P*<0.05 level.

The effects of soil physicochemical properties on soil enzyme activities were different. Results of the Monte Carlo test were shown in Table 3. The effects of soil physicochemical properties on soil enzyme activities were ranked as follows: soil temperature>soil water content>soil bulk density>soil total phosphorus>soil electrical conductivity>soil pH>soil organic carbon>soil total nitrogen. Among them, soil temperature, soil water content, soil bulk density, soil total phosphorus, soil electrical conductivity, and soil pH had significant effects on soil enzyme activities (P<0.05); while soil organic carbon and soil total nitrogen had little effect on soil enzyme activities.

Table 3 Results of the Monte Carlo test for soil physicochemical properties

Soil physicochemical property	*F* value	*P* value
Soil temperature	40.03	0.002
Soil water content	23.85	0.002
Soil bulk density	22.62	0.002
Soil pH	5.00	0.008
Soil electrical conductivity	5.20	0.006
Soil organic carbon	1.51	0.226
Soil total nitrogen	1.34	0.262
Soil total phosphorus	6.17	0.008

4 Discussion

4.1 Effects of sampling time and location on soil enzyme activities

Under the influence of solar radiation intensity, the thermal effect of forest edge, and the redistribution of canopy density, light, precipitation, and snowfall resources at different sampling locations in canopy gaps, soil enzyme activities had different responses in time and space. This study showed that with the change of sampling time, soil enzyme activities at different sampling locations were obviously dynamic. The result is similar to a recent study conducted by Wang et al. (2021). In this study, soil catalase, cellulase, sucrase, and acid phosphatase activities were relatively high from June to October. During the growing season, with the increase of temperature, the number of soil organisms increased, the metabolic level of litter and biological residues increased, and a large number of effective substrates were released, which promoted the rapid growth and reproduction of soil organisms and significantly increased soil enzyme activities (Xu et al., 2021). Ren et al. (2016) studied soil enzyme activities of different land use types on the Loess Plateau of China and found that soil catalase, sucrase, and acid phosphatase activities were the highest in June. Li et al. (2018) studied soil enzyme activities in poplar plantations and discovered that soil cellulase and catalase activities in the growing season were higher than those in the non-growing season.

Soil catalase, cellulose, and sucrase activities were generally high at closed canopy. This may be due to the dense plant roots, high rhizosphere exudates, and active soil organisms at closed canopy, which promoted the decomposition process of soil organic matter. This is consistent with the results of Xu et al. (2016). They found that soil catalase and acid phosphatase activities at gap center were lower than those at closed canopy, which was due to the decrease of substrate concentration and organic matter content at gap center. Soil urease is a key enzyme in the nitrogen cycle, which is of great significance to promote the nitrogen cycle and utilization (Singh et al., 2013). In this study, soil urease activity was different from other enzyme activities, which was relatively high in winter. Also, soil urease activity at gap center was higher than that at closed canopy. This was because approximately 90% of NH_4^+ and NO_3^- can be deposited on the surface by snowfall in winter (Chen et al., 2021; Liu et al., 2021), and the transformation of nitrogen in soil was relatively strong, resulting in higher soil urease activity under snow cover. Sardans et al. (2008) concluded that soil urease activity increased significantly when the soil temperature was

low in winter, which is consistent with the conclusion of this study.

In this study, soil enzyme activities were significantly affected by sampling time, indicating sampling time was the main driving factor affecting soil enzyme activities. The vegetation growth and organic matter inputs varied greatly at different sampling times, leading to changes in soil temperature and humidity (Brockett et al., 2012) that indirectly affect soil enzyme activities (Eslaminejad et al., 2020). Previous studies have shown that seasonality significantly affected soil enzymatic activities. For example, Wallenstein et al. (2009) reported that soil enzyme activities decreased due to cold winter, while Zuccarini et al. (2020) showed that soil enzyme activities decreased significantly in summer due to warming climate and limited soil moisture. The forest ecosystem in this study area is located in arid and semi-arid regions; thus, soil enzyme activities are more sensitive to seasonal changes. Furthermore, microclimatic changes caused by canopy gaps can alter the production and reaction rate of soil enzyme activity with seasonal fluctuations (Perreault et al., 2020).

4.2 Effects of sampling time and location on soil physicochemical properties

Due to the heterogeneity of canopy gaps, canopy gaps and their surroundings formed different microenvironments at different sampling time. In this study, soil temperature varied seasonally, and there were no significant differences in soil temperature at different sampling locations. Soil temperature at gap center was higher in October, December, and February because of the effect of seasonal snow cover on the preservation of soil heat. Soil water content in the non-growing season was higher than that in the growing season. This may be due to seasonal snow and snowmelt water penetrate the soil through the surface, and the frozen soil in the deep freeze state can retain water, resulting in higher soil water content during the non-growing season. With the increase of temperature, soil water content will penetrate into the soil pores, so that the soil at the early growing season maintains the water content (Niu and Yang, 2006; Ye and Lau, 2018). Soil bulk density can be used to characterize the soil compaction. Soil bulk density in winter was significantly higher than that in other seasons because of the high soil compaction under the deep freezing conditions. Soil bulk density was higher at gap center than that at closed canopy, the result is similar to a recent study conducted by Amolikondori et al. (2021). Soil pH characterized soil acidity, and soil pH at closed canopy was significantly higher than that at gap center. The increase in pH may be due to the fact that at closed canopy, plants have very dense roots that can absorb and consume large amounts of nutrients from the soil for plant growth. Litter decomposition will produce more organic acids, aggravate soil acidification, and reduce soil pH (De Schrijver et al., 2012; Wuyts et al., 2013; Wei et al., 2020). In this study, we found that soil organic carbon, soil total nitrogen, and soil total phosphorus changed little throughout the year, which was closely related to the role of seasonal snow cover. The existence of canopy gaps provided a relatively stable internal environment for snow cover and promoted the decomposition of litter at gap center in winter, thus the content of soil nutrient elements was in a high state (Christenson et al., 2010).

In this study, soil temperature was mainly affected by sampling time. Notably, soil total nitrogen was least affected by sampling time, while soil urease activity was most affected by sampling time. This may be due to the fact that soil enzyme activities were more sensitive to seasonal changes. Moreover, canopy gaps can influence the accumulation of organic matter on the forest surface by regulating organic matter decomposition, thereby changing the storage of carbon and nutrients. This is similar to the findings of Liu et al. (2018), who found that canopy gap affected microbial nutrients and their contributions to soil organic carbon and total nitrogen.

4.3 Interaction between soil enzyme activities and soil physicochemical properties

Soil enzyme activities were affected by many factors, such as soil organisms, soil temperature, soil water content, soil bulk density, and soil pH. This study showed that soil temperature, soil water content, soil total phosphorus, and soil pH were the important factors affecting soil enzyme activities. Soil temperature can affect soil enzyme activities directly or indirectly, and a suitable temperature had a promotive effect on soil enzyme activities (Wei et al., 2019). Soil temperature

was positively correlated with soil catalase, cellulase, sucrase, and acid phosphatase activities and negatively correlated with soil urease activity. Higher soil temperature in forest ecosystems was often accompanied by the input of fresh litter, which promoted the increase of soil catalase, cellulase, sucrase, and acid phosphatase activities (Li et al., 2020). Freeze–thaw cycles at low temperature promoted soil organisms (soil fauna, microorganisms, and plant roots) and plant macrofossil cells to release nutrients and intracellular enzymes into the soil, thereby improving soil urease activity to a certain extent (Tan et al., 2014). Soil water content was a key factor that mediates the coupling, cycling, and turnover of nutrients in soil (Zhou et al., 2021). In this study, soil water content was significantly positively correlated with soil urease activity and negatively correlated with other soil enzyme activities, which is similar to the results of Ma et al. (2013) and Wang et al. (2021). Other enzyme activities were higher in the growing season, and showed negative correlation with soil water content. A pervious study proved that soil pH can change the conformation of enzyme activity sites, the binding state between enzymes and soil particles, and the soil enzyme activities (Zhang et al., 2018). This study indicated that soil urease activity was significantly negatively correlated with soil pH, which is similar to the results of Fu et al. (2012) and Zhu et al. (2021). Soil total phosphorus was significantly positively correlated with soil cellulase and urease activities, which may be due to the increase of soil nutrient availability can promote soil microbial activities (Chen et al., 2003), thereby improving enzyme activities, and then higher soil enzyme activities can promote the release of soil nutrients to improve soil fertility.

5 Conclusions

Our results showed that sampling time and sampling location had a strong effect on soil enzyme activities and soil physicochemical properties in arid and semiarid forest ecosystems. The existence of canopy gaps caused the changes of snow cover patterns in winter and the difference in hydrothermal environments in the growing season, which made soil enzyme activities and soil physicochemical properties have obvious dynamics. Most of the enzyme activities were higher during the growing season at closed canopy than those at gap center. Soil urease activity was higher in December and February and it was higher at gap center than at closed canopy. Canopy gaps can control soil enzyme activities by regulating soil physicochemical properties in different seasons. The changes of soil enzyme activities were closely related to the fluctuation of soil physicochemical properties. Soil temperature and soil water content were the most significant variables affecting soil enzyme activities in the Tianshan Mountains. Therefore, this study provides essential information for maintaining the management and renewal of forest ecosystems by understanding the spatiotemporal variation of soil enzyme activities and soil physicochemical properties.

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